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Review

Methods for assessment of trunk stabilization, a systematic review

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ABSTRACT

Trunk stabilization is achieved differently in patients with low back pain compared to healthy controls. Many methods exist to assess trunk stabilization but not all measure the contributions of intrinsic stiffness and reflexes simultaneously. This may pose a threat to the quality/validity of the study and might lead to misinterpretation of the results. The aim of this study was to provide a critical review of previously published methods for studying trunk stabilization in relation to low back pain (LBP). We primarily aimed to assess their construct validity to which end we defined a theoretical framework operationalized in a set of methodological criteria which would allow to identify the contributions of intrinsic stiffness and reflexes simultaneously. In addition, the clinimetric properties of the methods were evaluated. A total of 133 articles were included from which four main categories of methods were defined; upper limb (un)loading, moving platform, unloading and loading. Fifty of the 133 selected articles complied with all the criteria of the theoretical framework, but only four articles provided information about reliability and/or measurement error of methods to assess trunk stabilization with test–retest reliability ranging from poor (ICC 0) to moderate (ICC 0.72). When aiming to assess trunk stabilization with system identification, we propose a perturbation method where the trunk is studied in isolation, the perturbation is unpredictable, force controlled, directly applied to the upper body, completely known and results in small fluctuations around the working point.

Contents

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1. Introduction

Trunk stabilization can be defined as maintaining control over trunk posture and movement, in spite of the disturbing effects of gravity and external and internal perturbations. Trunk stabilization is dependent on the passive (osteoligamentous), active (muscular) and neural sub-systems that contribute mechanically and in terms of acquiring and processing information to guide mechanical responses (Cholewicki and McGill, 1996). Stabilization of the trunk is required to control trunk movement during daily activities like standing, sitting, walking (MacKinnon and Winter, 1993; van der Burg et al., 2005), and can be limiting in performing precise arm and hand functions (Kaminski et al., 1995; Pigeon et al., 2000). Importantly, it has been hypothesized that inadequate trunk stabilization could contribute to low-back pain (LBP) through high tissue strains and/or impingements (Panjabi, 1992a,b).

Trunk stabilization is achieved differently in patients with low back pain (LBP) compared to healthy controls. These differences in trunk control have been interpreted as cause of the persistence of LBP (Hodges et al., 2009; MacDonald et al., 2010), and were even shown to be prospectively associated to LBP incidence (Cholewicki et al., 2005). Specifically, several studies have indicated longer reflex delays after an external mechanical perturbation of trunk posture in LBP patients than in controls (Magnusson et al., 1996; Radebold et al., 2000, 2001; Reeves et al., 2005). In apparent contrast, higher trunk stiffness, i.e. a higher mechanical resistance to such perturbations has also been reported (Hodges et al., 2009; van Dieën et al., 2003a). The latter is probably explained by findings of increased co-contraction of trunk musculature in patients compared to controls (van Dieën et al., 2003b). This has been interpreted as an adaptive response to enhance control over trunk movement and therewith prevent pain (Lund et al., 1991; van Dieën et al., 2003a). In fact, increased trunk stiffness through co-contraction could explain the longer delays found. With increased stiffness, the same mechanical disturbance will cause a smaller and slower deviation of trunk posture. Consequently, the disturbance would be perceived later and cause a slower and smaller increase in excitatory drive of the trunk musculature, resulting in an apparent increase in reflex delays. So paradoxically, the finding of an increased delay could actually reflect a functional, adaptive response to enhance trunk stability.

The above indicates that the contributions of intrinsic stiffness and reflexes to trunk stabilization need to be assessed simultaneously. This is possible using system identification techniques, which apply some form of external (often mechanical) perturbation and measure responses such as the trunk kinematics and trunk muscle EMG, from which properties of the stabilizing system, such as the intrinsic stiffness and reflex delays are estimated (Schouten et al., 2008; van der Helm et al., 2002). Many different methods using such an approach have been reported (Goodworth and Peterka, 2009; van der Helm et al., 2002; van Drunen et al., 2013). However, not all methods appear equally suitable. For example, not all take into account the intrinsic and reflexive contributions simultaneously. Furthermore, setups in some studies allow movement corrections in multiple joints (e.g. ankle, knee and hip), due to which experimental effects or between-group differences cannot be ascribed solely to the trunk.

To support interpretation of previous literature and to optimize methods for studying trunk stabilization in relation to LBP, we aimed to provide a critical review of previously published methods. We primarily aimed to assess their construct validity, to which end we defined a theoretical framework operationalized in a set of methodological criteria. This theoretical framework comprised the two criteria as introduced above as well as the criteria based on the requirement to allow for linear system identification, since a wide range of well-established techniques is available for this. The criteria are further detailed in the methods section. In addition, the clinimetric properties of the methods were evaluated, to assess their potential value in a clinical setting.

2. Methods

2.1. Theoretical framework

To evaluate the methods found in the literature, a theoretical framework was defined. In the introduction, two major criteria were already introduced: (1) the necessity of being able to simultaneously assess intrinsic and reflexive contributions to trunk stabilization and (2) the necessity to study the trunk in isolation.

To be able to assess the intrinsic and reflexive contributions to trunk control simultaneously through linear identification techniques, the method has to meet the following criteria:

Unpredictable	Disturbances must be unpredictable, since the presence of feed forward control to an expected perturbation renders it impossible to quantify reflexive and intrinsic components. System identification techniques assume a closed loop between the output forces and movements and the control input, e.g. the movement occurring upon perturbation of a static posture is assumed to be the basis for reflex inputs. When voluntary movements through feed forward control occur, this obviously would lead to a misinterpretation. To prevent feed forward control, an unpredictable perturbation should be used
Known Disturbance	To allow for system identification, the disturbance should be known (in terms of amplitude and timing). It is important to note that the disturbance is defined as the external input, which should be distinguished from the contact force between a device applying a perturbation and the subject, as this results from an interaction between device and subject
Perturbation Type	To permit the use of linear identification techniques, the disturbance should result in small fluctuations around a fixed working point, i.e. it should not entail large force differences and should not result

(continued on next page)

	in a large trunk displacements. To obtain sufficiently reliable information in spite of the limited trunk displacement and hence low signal to noise ratio, repeated perturbations are necessary. The perturbation should, therefore, not be a single impulse or step perturbation but preferably a multisine, repeated impulse or pseudo-random binary signal
Force Control	When perturbations are applied directly to the trunk, a force controlled perturbation instead of a displacement controlled perturbation should be used. With a fixed trunk displacement relative to the pelvis, the subject is unable to exert any influence over the resulting perturbation. Therefore, the subject will not be motivated to perform and it has been observed that subjects reduce their efforts to counteract position controlled perturbations already after several seconds (de Vlugt et al., 2003a,b)

The following criteria should be met to study the trunk in isolation:

Pelvic restraint	The pelvis of the subject should be restrained, forcing motion at the level of the spine, i.e. this assures that motion does not occur solely at the level of the pelvis
Point of application	The application of the perturbation should occur at the trunk or at the pelvis

These criteria will be used to assess the construct validity of the methods found in the literature. For a method to be considered valid, it should comply with all criteria with the exception of the ‘perturbation type’ criterion (hereafter referred to as necessary criteria). Although there are drawbacks to use certain perturbation types (for more information, see discussion), using the recommended perturbation types described earlier is not a requirement to be considered valid.

2.2. Literature identification

To identify relevant literature, we conducted a comprehensive search in PubMed and Embase from the beginning of the database up to September 2014. To be inclusive, we used a broad search as outlined in Appendix A. Only articles written in Dutch, German or English were included. Animal and cadaveric studies were excluded. No restrictions were applied to study design. Additionally, a snowball technique was applied by scanning the reference sections of all selected articles for potentially relevant articles that were not retrieved in the original search.

2.3. Study selection

The publications were included according to the following criteria which should be discernable from either the title or abstract text: (1) trunk stabilization was studied; (2) external mechanical perturbations were applied; (3) measurements included trunk kinematics and/or trunk muscle EMG. Eligibility of studies was determined independently by two researchers. If based on title and abstract uncertainty about eligibility of a study remained, the full text was reviewed. When discrepancies occurred between reviewers, the justifications for inclusion or exclusion of these articles was discussed until consensus was reached.

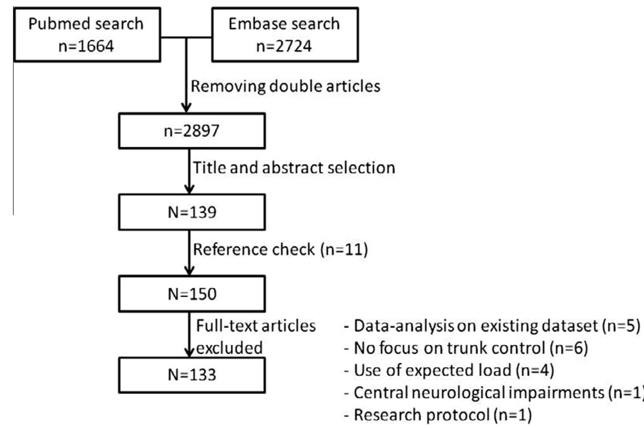

Fig. 1. Flowchart of the search strategy.

2.4. Data extraction

The following data were extracted from the included articles: author, year of publication, subject characteristics, muscle activity measurement and kinematic measurement techniques and perturbation technique. The construct validity of the methods was assessed independently by the two researchers with use of the theoretical framework as described above. When discrepancies occurred between reviewers, the justification for scoring on the set of methodological criteria was discussed until consensus was reached.

2.5. Assessment of methodological quality

If the objective of an included article comprised clinimetric assessment of reliability and/or measurement error of methods to assess trunk stabilization, the methodological quality of the study was assessed by the two reviewers using box B and C of an adapted version of the COnsensus-based Standards for the selection of Health Measurement INstruments (COSMIN checklist (Terwee et al., 2012), see Appendix B).

3. Results

3.1. Results of the search

A total of 133 articles were included (see Fig. 1 for a flowchart of the search and selection procedure).

3.2. Categorization

Based on the articles retrieved from the search, four main categories of perturbation methods were distinguished; trunk loading, trunk unloading, moving platform and upper limb (un)loading (see Table 1). Loading perturbations involve pushes or pulls applied at the upper back, thorax or pelvis. Unloading perturbation methods use a horizontal force applied to the subject’s thorax, upper back or pelvis by a cable from which a load is suspended and unexpectedly released. Alternatively, the subject applies a force, often controlled through visual feedback, on a cable that is unexpectedly released. During moving platform perturbations, subjects sit or stand on a platform, which is translated or tilted. Finally, in the upper limb (un)loading experiments the subjects stand while holding an

Table 1
Overview of studies included with assessment of validity based on the criteria listed in the methods section. The first columns contain information on subject and perturbation characteristics, EMG-measurements and kinematic measurements. The validity assessment scores can be found in the right thick outlined columns with 'X' = criterium is met, '–' = criterium is not met. ES = Erector Spinae, RA = Rectus Abdominis, EO = External Oblique, IO = Internal Oblique, MF = Multifidus, IC = Iliocostalis, LO = Longissimus, TrA = Transversus Abdominis, LD = Latisimus Dorsi.

Author (year)	Subjects	Perturbation magnitude	Trunk-EMG measurement	Trunk kinematics measurement	Unpredictable	Known disturbance	Perturbation Type	Force control	Pelvic restraint	Point of application
Trunk loading										
Andersen et al. (2004)	10 Healthy males	52 N (upper back)	Surface: ES (L3)	Potentiometer (upper back)	X	X	Step	X	X	X
Bazrgari et al. (2011a)	12 healthy subjects (6m, 6f)	10 mm (upper back)	Surface: ES (L1, L3), RA, EO	Displacement sensor and load cell at T8	X	X	Impulse	–	X	X
Bazrgari et al. (2011b)	3 healthy males	10 mm (upper back)	–	Displacement sensor and load cell at T8	X	X	Impulse	–	X	X
Bazrgari et al. (2012)	6 healthy subjects (3m, 3f)	10 mm (upper back)	–	Displacement sensor and load cell at T8	X	X	Impulse	–	X	X
Bazrgari et al. (2009)	2 healthy males, 1 LBP patient	±100 N (upper back)	Surface: MF(L5), IC (lumbar), LO (L1), RA, EO	Potentiometer and load cell at T8	X	X	Step	X	X	X
Borghuis et al. (2011)	21 healthy subjects	±123 N and ±80 N (upper back)	Surface: ES (L3), RA, EO	Angular velocity of the balance seat with gyroscopes	X	X	Impulse	X	–	X
Carlson et al. (1981)	4 healthy males	5 kg from 3 cm (upper back)	LO, MF, RA, EO	Force plate, angle between C7-L3 and vertical line with opto-electronic motion analysis system	X	–	Step	X	–	X
Chiang and Potvin (2001)	13 healthy males	20% and 30% of maximum isometric lateral bend moment (upper back)	Surface: EO, IO, ES (lumbar and thoracic), RA	Force transducer and displacement transducer from chest	X	X	Step	X	X	X
Cresswell et al. (1994)	6 healthy males	5 kg from 25 cm (upper back)	Fine-wire: RA, EO, IO, TrA, Surface: ES (L3)	Displacement of hip and shoulder with video-based analysis system	X	X	Step	X	–	X
van Drunen et al. (2013)	15 healthy subjects	±35 N (upper back)	Surface: RA, IO, EO, LO (lumbar and thoracic), IC (lumbar and thoracic)	Trunk kinematics with optotrak motion tracking system, with markers at L1–L5, T1, clustermarkers at T6 and T12 Displacement and contact force at T10 with position sensor and force sensor	X	X	Multi-sine	X	X	X
Dupeyron et al. (2010)	10 healthy males	50% of body mass (upper back)	Surface: ES, EO	–	X	X	Impulse	X	X	X
Eriksson Crommert and Thorstensson (2009)	11 healthy males	10 kg from 40 cm (upper back)	Fine-wire: TrA, EO, RA, ES (L3)	–	X	–	Step	X	X	X
Essendrop et al. (2002)	9 healthy subjects (4m, 4f)	52 N (upper back)	Surface: RA, TrA, ES (L3), IC (lumbar), EO, IO	Potentiometer from shoulder	X	X	Step	X	X	X
Gardner-Morse and Stokes (2001)	14 healthy subjects (8m, 6f)	7.5% and 15% of maximum effort (upper back)	–	Load cell and displacement transducer from T12	X	X	Single sine wave	X	X	X
Gilles et al. (1999)	5 healthy subjects (3m, 2f)	4% of body weight (pelvis)	Surface: abdominal and spinal muscles	Force plate, load cell from pelvis. Position pelvis with linear motors	X	X	Step	X	–	X
Granata et al. (2005)	18 healthy subjects (9m, 9f)	75 N (upper back)	Surface: RA, IO, EO, ES	Infrared motion sensors on S1, L5, T10, C7	X	X	Multi-sine	X	X	X
Granata et al. (2004a)	10 healthy males	6.2 ± 1.6, 9.3 ± 1.4 and 12.0 ± 1.7 N (upper back)	Surface: IO, EO, RA	Load cell and motion sensors at lower back	X	X	Impulse	X	X	X
Granata et al. (2004b)	21 healthy subjects (11m, 10f)	2.27 kg from 0.5 and 1 m (upper back)	Surface: RA, EO, IO, ES (L3)	Force plate, load cell and goniometers at T10 and SI	X	–	Step	X	–	X
Hendershot et al. (2013)	8 males with unilateral limb amputation and 8 healthy males	±5 mm anterior–posterior (upper back)	Surface: ES (L3), EO	Load cell, postural displacements with laser displacement sensor and servomotor encoder	X	X	Pseudorandom binary step	–	X	X

(*continued on next page*)

Table 1 (*continued*)

Author (year)	Subjects	Perturbation magnitude	Trunk-EMG measurement	Trunk kinematics measurement	Unpredictable	Known disturbance	Perturbation Type	Force control	Pelvic restraint	Point of application
Hendershot et al. (2011)	12 healthy subjects (6m, 6f)	±5 mm anterior–posterior (upper back)	Surface: ES (L1, L3), RA, EO	Load cell, encoder on servomotor-shaft, displacement sensor on frame at T8	X	X	Pseudorandom binary step	–	X	X
Herrmann et al. (2006)	10 healthy males	170 N (upper back)	Paraspinal muscles at L4	Load cell	X	–	Impulse	X	–	X
Hjortskov et al. (2005)	9 healthy males	52 N (upper back)	ES (L3/L4)	Potentiometer on wire attached to shoulder	X	X	Step	X	X	X
Hodges et al. (2009)	17 healthy subjects (9m, 8f) and 14 LBP patients (7m, 7f)	12–15% of body mass (upper back)	–	Trunk acceleration with force transducer from shoulder	X	X	Step	X	X	X
Kim et al. (2013a)	15 healthy males	9 kg from 30 cm (upper back)	Muscle thickness of EO, IO and TrA with brightness mode ultrasonography machines	–	X	X	Step	X	X	X
Krajcarski et al. (1999)	8 healthy males	12% or 24% of maximum isometric extensor moment (upper back)	Surface: ES (L3, T9), LD, RA, EO, IO	Force- and displacement transducer from shoulder	X	X	Step	X	X	X
Lariviere et al. (2010)	30 LBP patients (15m, 15f) and 30 healthy subjects (15m, 15f)	50% of the L5/SI extension moment (upper back)	Surface: MF (L5), IC (L3), LO (L1), RA, EO	Load cell and position trunk with potentiometer	X	X	Step	X	X	X
Lawrence et al. (2005)	6 healthy males	The subjects trunk weight at 20° (upper back)	Surface: LO (L3/L4), IC (L3/L4), LD (T9)	Dynamometer to measure trunk torque, trunk displacement with electromagnetic sensor at T9	X	X	Step	X	X	X
Lee et al. (2006)	17 healthy subjects	±70 N anterior (upper back)	Surface: RA, ES (lumbar), IO, EO	Electromagnetic position sensors at S1 and T10	X	X	Pseudorandom binary step	X	X	X
Magnusson et al. (1996)	11 LBP patients (7m, 4f) and 11 healthy subjects (7m, 4f)	2 kg from 45 cm (upper back)	Surface: ES (L3)	Force plate, load cell	X	X	Step	X	X	X
Masani et al. (2009)	12 healthy males	131–148 N in 8 different directions (upper back)	Surface: RA, EO, IO, ES (T9, L3)	–	X	–	"Impulse", manually applied	X	–	X
McGill et al. (1989)	3 healthy males	Unspecified (upper back)	–	Force plate	X	–	"Impulse", manually applied	X	–	X
McMulkin et al. (1998)	6 healthy males	9.35 N (lower back)	Surface: ES (L3), RA, EO, LD	–	X	X	Step	X	–	X
Miller et al. (2013)	8 male LBP patients and 9 healthy males	10 mm (upper back)	Surface: RA, ES	Load cell, displacement with encoder at servomotor	X	X	Pseudorandom binary step	–	X	X
Miller et al. (2010)	20 healthy subjects (10m, 10f)	3.97, 5.96, 7.67, 9, 10.21 N.s (upper back)	Surface: RA, ES	Trunk angle with inertial motion sensor at T6/T8	X	X	Impulse	X	X	X
Moorhouse and Granata (2005)	21 healthy subjects (10m, 11f)	±30 N (upper back)	–	Force transducer and trunk kinematics with optotrak sensors placed on S1 and T10	X	X	Multi-sine	X	X	X
Moorhouse and Granata (2007)	11 healthy males	±2 mm (upper back)	–	Force transducer and trunk displacement with optical encoder	X	X	Step	–	X	X
Navalgund et al. (2013)	13 LBP patients (7m, 6f) and 13 healthy subjects (7m, 6f)	±30 N (upper back)	Surface: ES (L3), MF (L5)	Torque transducer at motor shaft	X	X	Step	X	X	X
Omino and Hayashi (1992)	9 healthy males	10 or 5 kg (upper back)	Surface: ES (T12, L3)	Sway of T5 was measured	X	–	Step	X	–	X

Parcero (2000)	13 healthy males	12%, or 24% of maximal isometric extensor moment (upper back)	Surface: ES (L3, T9), EO, IO, RA	Force and displacement transducers at upper back	X	X	Step	X	X	X
Pedersen et al. (2004)	38 healthy subjects (8m, 30f)	58 N (upper back)	Surface: ES (L3)	Movement of upper back with potentiometer	X	X	Step	X	X	X
Pedersen et al. (2007)	37 healthy subjects	58 N (upper back)	Surface: ES (L3)	Movement of upper back with potentiometer	X	X	Step	X	X	X
Pedersen et al. (2009)	46 healthy females	58 N (upper back)	–	Movement of upper back with potentiometer	X	X	Step	X	X	X
Rietdyk et al. (1999)	10 healthy males	122 N (±1.3) (pelvis) and 108.7 N (±1.22) (upper back)	–	Force plate, segment positions with infrared emitting diodes	X	–	"Impulse", manually applied	X	–	X
Rogers and Granata (2006)	25 healthy subjects (12m, 13f)	±75 N (upper back)	Surface: RA, IO, EO, ES	Electromagnetic position sensors on SI, T10 and manubrium	X	X	Multi-sine	X	X	X
Santos et al. (2011)	15 healthy males	35% (upper back)	Surface: LO (L1), ICL (L3), MF(L5)	Potentiometer at T8	X	X	Step	X	X	X
Skotte et al. (2004)	19 healthy males	58 N (upper back)	Surface: ES (L3)	Movement of upper back with potentiometer	X	X	Step	X	X	X
Stokes et al. (2006)	21 LBP patients (11m, 10f) and 23 healthy subjects (15m, 8f)	5% or 10% of maximum effort in 80 ms in 5 different directions (upper back)	Surface: RA, IO, EO, LO, IC	Load cell for unset perturbation	X	X	Single sine wave	X	X	X
Stokes et al. (2000)	13 healthy subjects (7m, 6f)	7.5% or 15% of maximum effort in 80 ms in 5 different directions (upper back)	Surface: RA, IO, EO, LO, IC	Load cell for unset perturbation and displacement transducer at T12	X	X	Single sine wave	X	X	X
Thomas et al. (1998)	20 healthy subjects (10m, 10f)	5% of maximum isometric trunk extensor strength (upper back)	Surface: LO (thoracic), ES, EO, RA	Trunk kinematics with triaxial torso electro-goniometer	X	–	Step	X	X	X
Thomas et al. (1999)	20 healthy subjects (10m, 10f)	5% of maximum isometric trunk extensor strength (upper back)	Surface: LO (thoracic), ES, EO, RA	Trunk kinematics with triaxial torso electro-goniometer	X	–	Step	X	X	X
Thrasher et al. (2010)	13 healthy males	Varied between 92.2 N and 293 N (upper back)	–	Force transducer and trunk position with optotrak motion analysis system with markers at SIAS, SIPS, C6, T9, L3 and clustermarkers between C6 and T9 and T9 and L3	X	X	"Impulse", manually applied	X	–	X
Vera-Garcia et al. (2006)	14 healthy males	6.8 kg and 9.07 kg from 20 cm (upper back)	Surface: RA, EO, IO, LD, ES (T9, L3, L5)	Load cell and trunk kinematics with electromagnetic tracking instrument with transmitter at sacrum and receiver at T12	X	X	Step	X	X	X
Vera-Garcia et al. (2007)	12 healthy males	6.8 kg from 5 cm (upper back)	Surface: RA, EO, IO, LD, ES (T9, L3, L5)	Load cell and trunk kinematics with electromagnetic tracking instrument with transmitter at sacrum and receiver at T12	X	X	Step	X	X	X
Vette et al. (2014)	15 healthy males	39.9 ± 2.4 N in 8 different directions (upper back)	–	Load cell, position of T10 with motion capture system with markers 6 cm above and below T10	X	X	Impulse	X	–	X
Wilder et al. (1996)	11 LBP patients (6m, 5f)	2 kg from 45 cm (upper back)	Surface: ES, RA	Load cell at T4 and force plate	X	X	Step	X	X	X
Trunk unloading										
Brown and McGill (2009)	9 healthy males	5%, 10% and 15% of maximal isometric activation (upper back)	Surface: RA, EO, IO, LD, ES (T9, L3)	Angular displacements of lumbar spine with electromagnetic tracking instrument. Force on level L4/L5 and upper body cradle with force transducer	X	–	Step	X	X	X

(*continued on next page*)

Table 1 (*continued*)

Author (year)	Subjects	Perturbation magnitude	Trunk-EMG measurement	Trunk kinematics measurement	Unpredictable	Known disturbance	Perturbation Type	Force control	Pelvic restraint	Point of application
Brown et al. (2006)	14 healthy males	8 or 10.3 kg (upper back)	Surface: RA, EO, IO, LD, ES (T9, L3, L5)	Angular displacements of lumbar spine with electromagnetic tracking instrument	X	X	Step	X	X	X
Carlson et al. (1981)	4 healthy males	5 kg (upper back)	Surface: LO, MF, RA, EO	Force plate, angle between C7-L3 and vertical line with opto-electronic motion analysis system	X	–	Step	X	–	X
Cholewicki et al. (2002)	17 subjects (10m, 7f) with symptom free low back injury, and 17 healthy subjects (10m, 7f)	20% and 30% maximal isometric activation (upper back)	Surface: RA, EO, IO, LD, ES (lumbar and thoracic)	–	X	X	Step	X	X	X
Cholewicki et al. (1999)	10 healthy subjects	35% maximal isometric activation (upper back)	Surface: RA, EO, IO, LD, ES (lumbar and thoracic)	Displacement T9 with inductive sensor	X	X	Step	X	X	X
Cholewicki et al. (2010a)	20 subjects (14m, 6f)	100 N for men, 70 N for women (upper back)	–	Trunk acceleration at T5 with accelerometer	X	X	Step	X	X	X
Cholewicki et al. (2010b)	14healthy subjects (11m, 3f)	115 N for men, 80 N for women (upper back)	Surface: RA, EO, IO, LD, ES (lumbar and thoracic)	Trunk displacement at T5 with three-dimensional electromagnetic motion device	X	X	Step	X	X	X
Cholewicki et al. (2005)	292 subjects (144m, 148f)	108 N for men, 72 N for women (upper back)	Surface: RA, EO, IO, LD, ES (lumbar and thoracic)	–	X	X	Step	X	X	X
Cholewicki et al. (2000)	12 healthy subjects (6m, 6f)	35% maximal isometric activation (172 N ± 54 N) (upper back)	Surface: RA, EO, IO, LD, ES (lumbar and thoracic)	Displacement T9 with inductive sensor	X	X	Step	X	X	X
Eriksson Crommert and Thorstensson (2008)	11 healthy males	30, 50 and 70% of Maximal Voluntary Contraction (upper back)	Fine-wire: RA, EO, TrA, ES (L3)	–	X	X	Step	X	X	X
Kim et al. (2013b)	16 healthy females	8 kg (upper back)	Surface: MF (L4/L5)	Angular displacement with motion analysis system, markers at bilateral acromion, T1, SIPS, S2	X	X	Step	X	X	X
Magnusson et al. (1996)	11 LBP patients (7m, 4f), 11 healthy subjects (7m, 4f)	Unspecified (upper back)	Surface: ES	Load cell, Force plate	X	–	Step	X	X	X
Marshall et al. (2009)	12 subjects with ankle instability (5m, 7f) and 12 healthy subjects (5m, 7f)	65 N for men and 40 N for females (upper back)	Surface: ES (L4), RA	Angular displacement, force output and movement velocity with dynamometer	X	X	Step	X	X	X
Radebold et al. (2000)	17 LBP patients (12m, 5f) and 17 healthy subjects (12m, 5f)	65 N and 108 N for men and 40 N and 72 N for women (upper back)	Surface: RA, EO, IO, LD, ES (T9, L3)	Undefined how trunk angle was measured	X	X	Step	X	X	X
Radebold et al. (2001)	16 LBP patients (1f, 15m) and 14 healthy subjects (1f, 13m)	Undefined (upper back)	Surface: 12 major trunk muscles	Undefined how trunk angle was measured	X	X	Step	X	X	X
Reeves et al. (2005)	35 LBP patients (27m, 8f) and 32 healthy subjects (22m, 10f)	65 N for males, 40 N for females (upper back)	Surface: RA, EO, ES (T9, L5)	–	X	X	Step	X	X	X

Reeves et al. (2009)	6 healthy subjects (4m, 3f)	20 N (upper back)	–	Motion capture system with markers at T9 and L4/L5	X	–	Step	X	X	X
Moving platform										
Blomqvist et al. (2014)	43 healthy subjects and 56 subjects with intellectual disability	3,5 cm, 55 cm/s, 200 cm/s^2 posterior	Surface: ES (L4)	Accelerometer on platform	X	X	Step	X	–	–
Boudreau et al. (2011)	10 healthy subjects	8 cm, 270 cm/ms anterior and posterior and 10°, 120°/ms anterior and posterior tilt	Surface: ES (T12, L2, L4), EO	–	X	X	Impulse	X	–	–
Carpenter et al. (1999)	17 healthy subjects (8m, 9f)	7.5°, 50°/s tilts in 12 directions	Surface: paraspinals	Force plate, angular velocity sternum with transducers	X	X	Step	X	–	–
Carpenter et al. (2005)	12 healthy males	8 cm, 0.25 m/s, 1.7 m/s^2 and 60 cm, 0.25 m/s, 1.3 m/s^2 anterior and posterior	Surface ES (L4), Fine-wire: RA	Accelerometer on platform, rotations of trunk with opto-electronic motion-analysis system	X	X	Impulse	X	–	–
Chen et al. (2014)	19 healthy subjects (12m, 7f)	70 mm, 500 mm/s anterior and posterior and 7°, 50°/s anterior and posterior tilt	Surface: paraspinals (cervical, lumbar (L2/L3) and thoracic), RA	Kinematics with motion analysis system with 42 markers at bony landmarks	X	X	Step	X	–	–
Cort et al. (2013)	7 healthy males	4 cm, 4 m/s^2 left and right	Surface: RA, EO, IO, ES (lumbar and thoracic), MF, LD	Accelerometer on platform, kinematics with active marker system with clustermarkers at sacrum and T9	X	X	Step	X	X	X
Cote et al. (2009)	10 patients with whiplash-associated disorder (5m, 5f) and 10 healthy subjects (5m, 5f)	15 cm in 500 ms anterior and posterior	Surface: paraspinals (cervical, thoracic and lumbar), trapezius, RA, EO	Kinematics with motion analysis system with markers on right scapula, C7, T6, T1, T8, T12, L1, S1, SIPS, sacrum, sternum, acromia	X	X	Impulse	X	X	X
Diener et al. (1988)	10 healthy subjects (5m, 5f)	1.2, 3.6, 6, 9 and 12 cm, 15 cm/s and 6 cm, 10, 15, 25 and 35 cm/s posterior	Surface: RA, ES	Force plate, Potentiometer on platform, hip angle with computerized movement analysis system	X	X	Impulse	X	–	–
Dobosiewicz (1997)	394 patients with adolescent scoliosis (83m, 311f) and 70 healthy children (10m, 60f)	8° left and right tilt	Surface: ES (T8, L1, L3)	–	X	X	Step	X	–	–
Farahpour et al. (2014)	10 patients with adolescent idiopathic scoliosis and 10 healthy subjects	10% of body mass from 70 cm was dropped to pull the platform	Surface: ES (L3, T10)	–	X	X	Step	X	–	–
Forssberg and Hirschfeld (1994)	8 healthy subjects (4m, 4f)	8 cm, 36 cm/s in 4 directions and 8°, 50°/s anterior and posterior tilt	Surface: ES (L3–L4 and T8–T9)	Platform and trunk displacement at C7, T10, L5, SIAS, TM with three-dimensional electromagnetic motion device	X	X	Step	X	–	X
Goodworth and Peterka (2009)	14 healthy subjects (7m, 7f)	±4° left and right tilt	–	Hip angular position, rotations between C6 and T3 and knees with potentiometer	X	X	Pseudorandom ternary step	X	X	X
Goodworth and Peterka (2010)	3 subjects with bilateral vestibular loss (2m, 1f) and 8 healthy subjects (3m, 5f)	±4° left and right tilt	–	Hip angular positon, rotations between C6 and T3 and knees with potentiometer	X	X	Pseudorandom ternary step	X	X	X

(*continued on next page*)

Table 1 (*continued*)

Author (year)	Subjects	Perturbation magnitude	Trunk-EMG measurement	Trunk kinematics measurement	Unpredictable	Known disturbance	Perturbation Type	Force control	Pelvic restraint	Point of application
Gruneberg et al. (2004)	5 healthy subjects (3m, 2f)	7.5°, 60°/s tilt in 6 directions	Surface: paraspinals (L1–L2)	Force plate, potentiometer on platform, angular velocity sternum with transducers	X	X	Step	X	–	–
Henry et al. (1998)	7 healthy subjects (3m, 4f)	9 cm, 35 m/s in 12 directions	Surface: RA, ES	Force plate	X	X	Impulse	X	–	–
Henry et al. (2006)	24 healthy subjects (12m, 12f) and 26 LBP patients (12m, 14f)	9 cm, 43 cm/s, 127 cm/s^2 in 12 directions	–	Force plate, trunk positions with infrared camera system and reflexive markers	X	X	Impulse	X	–	–
Horak et al. (1989)	20 healthy subjects	1.2, 3.6, 6, 9, 12 cm, 10, 15, 35 cm/s posterior	Surface: RA, lumbar paraspinals	Force plate, potentiometer attached to hips	X	X	Impulse	X	–	–
Horak and Nashner (1986)	10 healthy subjects (4m, 6f)	13 cm/s in 250 ms anterior and posterior	ES (L4–L5), RA	Force plate (strain gauges) and hip angle with single-frame analysis of videotaped recordings with white markers	X	X	Impulse	X	–	–
Horak et al. (1990)	6 healthy subjects and 4 subjects with vestibular loss	6 cm, 15 cm/s and 1.2 cm, 6 cm/s and 12 cm, 35 cm/s anterior and posterior	Surface: RA, lumbar paraspinals	Force plate, potentiometer attached to hips	X	X	Impulse	X	–	–
Huang et al. (2001)	8 healthy males	10 cm, 0.5 m/s, 10 m/s^2 left and right	–	Force plate, optoelectronic movement analysis system with cluster markers on L1 and left thigh	X	X	Impulse	X	–	–
Inglis et al. (1994)	9 patients with lower extremity neuropathy (6m, 3f) and 8 healthy subjects	6 cm, 10 cm/s, 15 cm/s, 25 cm/s, 35 cm/s and 1.2 cm, 3.6 cm, 6 cm, 9 cm, 12 cm at 15 cm/s posterior	Surface: lumbar paraspinals	Force plate	X	X	Impulse	X	–	–
Jacobs et al. (2011)	24 LBP patients (13m, 11f) and 21 healthy subjects (8m, 13f)	9 cm, 43 cm/s, 127 cm/s^2 in 12 directions	Surface: ES (L1, L3), EO, IO, RA	–	X	X	Impulse	X	–	–
Jones et al. (2012)	20 LBP patients (9m, 11f) and 21 healthy subjects (8m, 13f)	43 cm/s, 127 cm/s^2 in 12 directions	Surface: RA, IO, EO, ES (L1 and L3)	Force plate, 3D kinematic data of hip and trunk angle with passive marker system	X	X	Impulse	X	–	–
Kamper et al. (1999)	4 male tetraplegics, 4 male paraplegics and 5 healthy males	12° and 23° left tilt	–	Load cells for measuring axial forces between platform and wheelchair	X	X	Step	X	–	X
Keshner et al. (2004)	10 healthy subjects	10 cm, 15 cm/s and 3 m, 3.7 m/s anterior posterior	Surface: paraspinals (L2–L3 and (T4–T5), RA	Strain gauge sensors under platform, potentiometer attached to hip	X	X	Impulse	X	–	–
Keshner et al. (1988)	11 healthy subjects	3 cm in 125 ms or 250 ms anterior posterior	–	Trunk angular position with video motion analysis system with markers on C7 and great trochanter	X	X	Impulse	X	–	–
Mok and Hodges (2013)	20 healthy subjects (11m, 9f)	0.7° in 250 ms, 1.8° in 300 ms and 3.2° in 400 ms anterior posterior	–	Force plate	X	X	Step	X	–	–
Newcomer et al. (2002)	20 LBP patients (9m, 11f) and 20 healthy subjects (9m, 11f)	1.25∗patients height/72 in 300 ms and 2.25∗patients height/72 in 400 ms and 8° in 80 ms anterior posterior	Surface: ES (L4/L5), RA	–	X	X	Impulse	X	–	–

Notzel et al. (2011)	8 female LBP patients and 12 healthy females	Undefined left and right and anterior posterior	Surface: ES, RA, IO, EO, MF	–	X	X	Impulse	X	–	–
Oddsson et al. (1999)	8 healthy males	0.11 m in 300 ms anterior posterior	Surface: ES (L3), RA	Accelerometer at L3 and hip and shoulder kinematics in sagittal plane with video-based motion analysis	X	X	Impulse	X	–	–
Parnianpour et al. (2001)	18 healthy males	2.5 cm with 3 cm/s and 4°, 2.4°/s tilt in 3 directions	–	Force plate, potentiometers on hips and shoulders	X	X	Impulse	X	–	–
Perret and Robert (2004)	13 scoliotic children and 3 healthy children	8° left and right tilting	Surface: paraspinals (T7–10 and L2–3)	Accelerometer at cervicothoracic junction level	X	X	Step	X	–	–
Preuss and Fung (2008)	13 healthy males	150 mm, 0.45 m/s in 8 directions	Surface: RA, IO, EO, thoracic paraspinals, ES (thoracic and lumbar), MF	Force plate, position-data of trunk with Vicon motion analysis system with markers at T1–T6, T7–T12, L1–L5 and pelvis	X	X	Impulse	X	X	X
Sayenko et al. (2012)	21 healthy subjects (14m, 7f)	10°, 50°/s, 200°/s backward tilt	Surface: ES	Displacement of C7 and great trochanter with laser displacement sensors	X	X	Step	X	–	–
Zedka et al. (1998)	5 healthy subjects (3m, 2f)	10°, 20°, 8°/s and 26°/s in four directions	Surface: ES (T10, L3), EO, IO, RA, LD	Angular displacement of platform with potentiometer	X	–	Step	X	X	X
Upper limb (un)loading										
Aruin and Latash (1995)	7 healthy males	2,2 kg unloading	Surface: RA, ES	Force plate, goniometers for hip angles	X	X	Step	X	–	–
Brown et al. (2003)	11 healthy males	6,8 kg unloading	Surface: ES (lumbar and thoracic), EO, RA	Force plate	X	–	Step	X	–	–
Dupeyron et al. (2013)	30 LBP patients (19m, 11f)	2 kg from 40 cm	Surface: ES (L3), EO, RA	Accelerometer on box to determine perturbation onset	X	–	Step	X	–	–
Gregory et al. (2008)	13 healthy subjects (6m, 7f)	6,78 kg from 2 cm	Surface: ES (thoracic and lumbar), RA, EO	Force plate	X	–	Step	X	–	–
Grondin and Potvin (2009)	15 healthy females	5 kg from 2.5 cm	ES (thoracic and lumbar), EO, IO	Goniometers at L5 and L3	X	–	Step	X	–	–
Hodges et al. (2001)	5 healthy males	2 kg with a wire attached to hands	Fine-wire: TrA, IO, EO. Surface: RA, ES (L4)	Angle between T12 and S1 and iliac crest and S1 with opto-electronic system and infrared markers	X	–	Step	X	–	–
Hwang et al. (2008)	38 healthy subjects (21m, 17f)	1 kg from minimum of 0.5 m	Surface: ES (T12-L1), MF L5-SI)	Force plate, Electromagnetic tracking system with sensors at T1 at L1 and S1	X	–	Step	X	–	–
Lavender and Marras (1995)	4 healthy males	5.4 kg from 110 cm	Surface: ES (L3/L4), LD, RA, EO	Force plate	X	–	Step	X	–	–
Lavender et al. (1993)	4 healthy males	53.4 N	Surface: LD, ES, RA, EO, IO	Force plate, lumbar motion (L5-S1) with a lumbar motion monitor	X	–	Step	X	–	–
Lavender et al. (1989)	11 healthy males	6 kg from 78.4 cm	Surface: LD, ES (L3), RA, EO	–	X	–	Step	X	–	–
Lavender et al. (2000)	18 healthy subjects (8m, 10f)	7.5% maximal trunk extension force from 1m	Surface: LD (T7 and T10), ES (L3/L4), EO, RA	Force plate, trunk positions with magnetic motion measurement system with sensors on T1, L1 and S1.	X	X	Step	X	–	–
Lee et al. (2011)	10 healthy subjects (5m, 5f)	1 kg from 30 cm	Fine-wire: MF, LO (T5, T8, T11)	Force plate	X	–	Step	X	–	–
Leinonen et al. (2002)	20 LBP patients (15m, 5f) and 15 healthy subjects (10m, 5f)	0.68 kg from eye height	Surface: ES (L12-L1), MF (L5-S1)	Force plate and marker switch on load	X	–	Step	X	–	–

(continued on next page)

Table 1 (*continued*)

Author (year)	Subjects	Perturbation magnitude	Trunk-EMG measurement	Trunk kinematics measurement	Unpredictable	Known disturbance	Perturbation Type	Force control	Pelvic restraint	Point of application
Leinonen et al. (2003)	20 healthy subjects (10m, 10f)	0.69 kg from minimum of 0.5 m	Surface: ES (L12-L1), MF (L5-S1)	Marker switch on load	X	–	Step	X	–	–
MacDonald et al. (2010)	13 LBP patients (6m, 7f) and 14 healthy subjects (8m, 6f)	1 kg from eye height	Fine-wire: MF (L5, deep and superficial)	Load contact with box started EMG recording	X	–	Step	X	–	–
Mannion et al. (2000)	12 healthy subjects (6m, 6f)	2, 4 and 6 kg from 10 cm for men, 40% less for women	Surface: ES (T10 and L3), RA, EO	Force plate, Load cell, angle between L1 and S1 with motion analysis device	X	–	Step	X	–	–
Marras et al. (1987)	12 healthy males	2.27, 4.54, 6.8 and 9.07 kg from 83.8 cm	Surface: LD, ES, RA	–	X	X	Step	X	–	–
Mawston et al. (2007)	30 healthy males	100 N	ES (L4/5 and T9), RA, IO, EO	Hip joint angle with digital video camera with markers on lateral femoral condyle, great trochanter and sacrum and for lumbosacral angle on L1 and sacrum	X	–	Step	X	–	–
McGill et al. (1989)	3 healthy males	Undefined	–	Force plate	X	–	Impulse, manually applied	X	–	–
McMulkin et al. (1998)	6 healthy males	18.8 N	Surface: ES (L3), RA, EO, LD	–	X	X	Step	X	–	–
Mok et al. (2011)	11 LBP patients and 11 healthy subjects	1 kg from 30 cm	–	Force plate, Position of lumbar spine with electromagnetic analysis system with markers at L1, S1 and IC	X	–	Step	X	–	–
Moseley et al. (2003)	7 healthy subjects (5m, 2f)	1% body mass from eye height	Fine-wire: MF, TrA. Surface: ES (T7)	–	X	X	Step	X	–	–
Mullington et al. (2009)	19 healthy subjects (12m, 7f)	1.25 kg from undefined height	Surface: ES (T12, L4), RA (L4)	Accelerometers at shoulder and T12	X	X	Step	X	–	–
Ramprasad et al. (2011)	25 LBP patients (18m, 7f)	3 kg from 8 cm	Surface: RA, ES (L3–4)	Force plate	X	–	Step	X	–	–
Ramprasad et al. (2010)	25 LBP patients (18m, 7f) and 25 healthy subjects (15m, 10f)	3 kg from 8 cm	Surface: RA, ES (L3–4)	Force plate	X	–	Step	X	–	–
Shu et al. (2007)	10 healthy males	30% of maximal voluntary contraction	Surface: MF, LO (L2)	–	X	–	Step	X	–	–
Sung and Park (2009)	36 LBP patients (18m, 18f)	0.7 kg from 1.8 m	–	Force plate and impact force with load cell	X	X	Impulse	X	–	–
Sung et al. (2004)	46 LBP patients (22m, 24f)	6.4 N	Surface: ES (L3) MF	Onset perturbation with load cell	X	X	Impulse	X	–	–
Voglar and Sarabon (2014)	24 healthy subjects (15m, 9f)	8% of body weight loading or 25% of maximal voluntary force unloading	Surface: RA, EO, IO, ES, MF	Force sensor at hand-handle	X	X	Step	X	–	–
Wagner et al. (2005)	10 healthy males	Unspecified	–	Load cell, trunk kinematics with high-speed video system with markers at shoulders, hip, between L5 and C7	X	X	Step	X	–	–
Wilder et al. (1996)	6 LBP patients (4m, 2f) and 16 healthy subjects (6m, 10f)	6.4 N	Surface: ES (L3)	Onset perturbation with load cell	X	–	Step	X	–	–

empty receptacle in which a load is dropped. In some studies, the arms of the subjects are attached to a wire with a load on the other end which is suddenly dropped, resulting in a sudden force. In one setup, subjects hold a weighted box, which is suddenly pulled upward by a cable. In another setup, subjects hold a balloon attached to a load; popping the balloon results in sudden unloading.

LBP patients were included in 26 out of 133 articles distributed over the four different categories of perturbation methods (7 loading, 5 unloading, 5 moving platform, 9 upper limb (un)loading). None of these studies reported adverse events. A wide variety of perturbation magnitudes has been used across the four categories. Also, a wide variety in measurement methods of muscle activity and kinematics has been used. EMG measurements varied from no measurements in 25 articles to fine-wire and surface EMG measurements in several trunk muscles. Kinematic measurements varied from no measurements in 20 articles, to force plate and loading cell measurements to full 3 dimensional motion analyses. Detailed information on subject characteristics, perturbation magnitudes, EMG and kinematic measurements can be found in Table 1.

Fifty of the 133 included articles described a method that complied with all necessary methodological criteria (see Table 1). All methods complied with the "unpredictable" criterion. In all but seven studies, force control was used. None of the upper limb (un)loading articles met with the "pelvic restraint" and "point of application" criteria.

3.3. Trunk loading perturbations

Among the 55 articles describing trunk loading perturbations, 32 complied with all necessary criteria (see Table 1). Ten articles did not comply with the "known disturbance" criterion, predominantly due to unknown onset of perturbation (i.e. timing). All but seven articles complied with the "force control" criterion. In 13 articles, the pelvis was not restrained. And all articles complied with the "point of application" criterion. Four types of perturbations were applied: in 14 studies, an impulse was applied, in 30 a step, in four a pseudorandom binary step, in three a single sine wave and in four a multi-sine.

3.4. Trunk unloading perturbations

Of the 17 articles describing trunk unloading perturbations, 13 complied with all necessary criteria (see Table 1). Four articles failed to comply with the "known disturbance" criterion while one did not restrain the pelvis. All studies applied step perturbations.

3.5. Moving platform perturbations

Five out of 35 articles describing moving platform perturbations complied with all necessary criteria (see Table 1). In one study, the timing of the disturbance was not known due to manual application of the perturbation. In only six articles, the pelvis was restrained. In 27 articles subjects stood on the platform and therefore these did not comply with the "point of application" criterion. Two types of perturbations were applied: in 15 articles a platform translation was applied, which equals a force impulse on the subject, while in the remaining 20, platform rotations/tilts were performed, which equals a step perturbation.

3.6. Upper limb (un)loading

Because all perturbations in this category were applied to the upper limbs, none of the 31 articles complied with the "point of application" criterion (see Table 1). Furthermore, none of the methods described used a pelvic restraint. For 21 articles, the perturbation was unknown due to an unknown timing. Three studies applied impulse perturbations while the others applied step perturbations.

3.7. Clinimetric assessment

Reliability was tested in three of the included studies (Hodges et al., 2009; Santos et al., 2011; Voglar and Sarabon, 2014) and one study which used data from two previously published studies (Hendershot et al., 2012). Measurement error was tested in three studies (Hendershot et al., 2012; Santos et al., 2011; Voglar and Sarabon, 2014). Hendershot et al. (2012) described a sudden-loading task with standing subjects, who wore a wooden or plastic harness attached to a servo-motor, which applied pseudorandom binary anterior–posterior position perturbations. Within-day reliability, between-day reliability and measurement error were calculated for both harnesses. For both the wooden and plastic harness, the within-day reliability of trunk stiffness (0.84 and 0.90 respectively) and effective mass (0.91 and 0.95 respectively) were good (Portney and Watkins, 2000). Reflex gain (0.55 and 0.85), maximum reflex force (0.65 and 0.85) and timing of maximum reflex force (0.84 and 0.86) were found less reliable and within-day reliability was found superior to between-day reliability (mean ICC 0.42, range [0.19–0.72]). The plastic harness also seemed consistently more reliable than the wooden version.

In the study by Santos et al. (2011), subjects were seated with their pelvis restrained. A sudden load was applied via a cable connected to a load cell and attached to a harness worn by the subjects. Three different ways of analyzing the reflex latencies and amplitudes were used. Reliability of the method was poor to moderate (ICC 0–0.62).

Hodges et al. (2009) applied sudden loading in a semi-seated position via a cable attached to a thorax harness. Reliability was assessed in 10 subjects. For forward perturbations, the ICC's for stiffness, damping and mass were moderate at 0.67 (range [0.12–0.91]), 0.72 (range [0.20–0.92]) and 0.67 (range [0.12–0.91]) respectively. For backward perturbations, the ICC's for stiffness, damping and mass were poor to moderate at 0.60 (range [0.00–0.88]), 0.57 (range [−0.43 to 0.87]) and 0.31 (range [−0.36 to 0.77]) respectively.

In Voglar and Sarabon (2014), postural reflex delays to unexpected loading and unloading of the arms were assessed in a standing unrestrained position. The response of five trunk muscles was evaluated, for which a good intra-session (ICC = 0.79, range [0.56–0.96]) and moderate (ICC = 0.64, range [0.43–0.84]) inter-session reliability were reached.

The methodological quality of these four articles was assessed with use of Box B and C of the COSMIN checklist (Appendix B). Hendershot et al. (2011) scored 'good', Santos et al. (2011) 'fair' and Voglar and Sarabon (2014) "poor" on both methodological qualities (see Table 2 for the results). Hodges et al. (2009) scored "poor" on reliability.

4. Discussion

None of the articles from the upper limb (un)loading category complied with all the necessary criteria. One of the major problems with upper limb (un)loading is the point of application. When the perturbation is delivered through the hands/arms, the true extent of the perturbation to the trunk (i.e. timing and amplitude) is unknown. Therefore, studying trunk stabilization through upper limb (un)loading is not the most appropriate method.

Applying the perturbation by a moving/tilting platform is only suitable if the pelvis of the subject is restrained in either a seated or a standing position. However, applying the perturbation in a

Table 2
Scores of the COSMIN-criteria. E = Excellent, G = Good, F = Fair, P = Poor. For a further explanation of the different criteria of the Cosminlist, see Appendix B.

Reliability criteria	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12	B13	B14	Total
Hendershot et al. (2012)	**G**	**G**	**G**	**E**	**E**	**E**	**G**	**E**	**E**	**E**	**G**	–	–	–	G
Santos et al. (2011)	**G**	**G**	**F**	**E**	**E**	**E**	**G**	**E**	**E**	**E**	**G**	–	–	–	F
Hodges et al. (2009)	**G**	**G**	**P**	**E**	**E**	**E**	**G**	**E**	**E**	**E**	**G**	–	–	–	P
Voglar and Sarabon (2014)	**G**	**G**	**P**	**E**	**E**	**E**	**G**	**E**	**E**	**E**	**G**	–	–	–	P
Measurement error criteria	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11				Total
Hendershot et al. (2012)	**G**	**G**	**G**	**E**	**E**	**E**	**G**	**E**	**E**	**E**	**E**				G
Santos et al. (2011)	**G**	**G**	**F**	**E**	**E**	**E**	**G**	**E**	**E**	**E**	**E**				F
Voglar and Sarabon (2014)	**G**	**G**	**P**	**E**	**E**	**E**	**G**	**E**	**E**	**E**	**E**				P

standing position has some drawbacks. For example, Goodworth and Peterka (2009) applied perturbations to standing subjects through a sideways tilting platform, but had to discard a large part of their measurements, due to the inability of many subjects to keep their knees locked. Bending of the knee(s) made the extent of the perturbation to the trunk due to the moving platform unknown.

Many of the methods applying trunk unloading perturbations complied with all the necessary methodological criteria. However, the use of a step perturbation is inherent to unloading and has two potential drawbacks. First, to reach the desired level of reliability, either many trials or high levels of pre-load (% MVC) are required. The combination of many trials and high pre-loads might not be feasible, especially not in LBP patients, who might not be able to produce many repetitions with high force levels without pain. The second potential drawback of step perturbations is the difficulty in making the perturbations truly unpredictable. Unloading often occurs within a certain time period after reaching a desired level of pre-load. However, if this time period is short, subjects are still able to anticipate on the perturbation by, for example, co-contracting. Therefore, to negate this possibility, long periods of uncertainty must be included. These long periods of uncertainty coupled with high levels of pre-load can be exhaustive and might not be feasible when studying certain patient populations.

Of the methods applying trunk loading perturbations, many complied with all the necessary methodological criteria. However, when applying loading perturbations, the perturbation should not be delivered manually by the experimenter (by e.g. dropping a weight). This makes the timing of the perturbation (i.e. the onset) uncertain, in turn, making estimates of reflex delays impossible and/or inaccurate. Putting a force sensor between the dropped load and the subject may not be sufficient as this is a measurement of the interaction between the subject and the load, where the force sensor introduces noise into the estimation of the onset of the perturbation. Among the methods using loading perturbations, different perturbation types were applied: single sine waves, step, impulse and pseudorandom binary perturbations and multi-sines. Single sine waves are only appropriate when the period of the sine wave is shorter than the shortest muscle reflex delay and when the onset of the sine wave is unpredictable. Otherwise, subjects are able to respond voluntarily and the reflexive and voluntary activation are no longer distinguishable. Both step and impulse perturbations are suitable but require sufficient power (i.e. large perturbation forces) and/or many repetitions for sufficient reliability. These potential drawbacks can be circumvented with either a pseudorandom binary signal or with multi-sines, where trials can last as long as needed, without becoming predictable. A drawback of multi-sines and pseudorandom sequences is the "unnatural" nature of the task, as the perturbation is continuous and never occurs from an unperturbed initial condition. An added benefit of multi-sines is that power can be selectively included (at selected frequencies).

Only four of the included articles performed a clinimetric assessment by determining the reliability of the method and only two of those complied with all the methodological criteria (Santos et al., 2011; Hodges et al., 2009). The ICC was used as a measure of reliability and ranged from poor (ICC 0) to moderate (ICC 0.72). Besides these studies on reliability, nothing is known about the other clinimetric properties. Also, only limited studies have been performed on LBP patients and the ability of most methods to differentiate between healthy subjects and LBP patients is still unknown. Furthermore, specific information on included LBP patients are sometimes lacking (e.g. acute or chronic, resubmission during testing, referral pain), which hampers the interpretation of results and the assessment of the clinical value of the method.

Considering the methodological criteria and the arguments outlined above, a limited selection of articles describe methods that can be recommended when aiming to simultaneously assess the intrinsic stiffness and reflexive components of trunk stability with use of system identification, both in the trunk loading (Granata et al., 2005; Lee et al., 2006; Moorhouse and Granata, 2005; Rogers and Granata, 2006; van Drunen et al., 2013) and in the moving platform category (Cort et al., 2013; Cote et al., 2009; Preuss and Fung, 2008). None of these articles include a clinimetric evaluation and it is therefore recommended that future research focusses on determining the reliability and other clinimetric assessments of these methods.

Several limitations of this review have to be discussed. Beside the ever present publication bias, a certain amount of selection bias may be present as well. However, a snowball procedure was applied to minimize this effect. Furthermore, there is a wide variety of clinimetric assessments that are important when evaluating the quality of an instrument (e.g. internal consistency, content validity, structural validity, responsiveness) that we have not addressed. We have mainly focused on the construct validity for it is the overarching concern of validity research, subsuming all other types of validity evidence. Finally, one of the included studies (van Drunen et al., 2013) was performed by researchers from the same research group as the authors of the current review. Therefore, a certain amount of bias cannot be excluded.

In conclusion, because of the wide variety in methods and the lack of validation and reliability studies, it is difficult to compare studies and the interpretation in terms of the underlying mechanisms of trunk stabilization is limited. Therefore there is a need for standardization and clinimetric evaluation. When considering construct validity, in line with the methodological criteria as outlined in the methods section, we propose a method where the trunk is studied in isolation, i.e. the pelvis is restrained and the perturbation is applied directly to the upper body, either through the trunk or pelvis. Furthermore, the perturbation should be unpredictable, force controlled and completely known (in terms of amplitude and timing). Finally, the perturbation should result in small fluctuations around a fixed working point. To obtain sufficient reliability, a multi-sine, repeated impulse or pseudorandom binary signal is preferred. A higher standardization of methods to study trunk control will contribute to a higher quality of research and enable better comparisons to be made between studies.

Conflicts of interest

The authors declare that there are no conflicts of interest.

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Appendix A. Search strategy

Search conducted in PubMed and Embase on September 1st, 2014: ((perturbat∗[tiab] OR "sudden load∗"[tiab] OR "quick release"[tiab] OR "external load∗"[tiab] OR "Unload∗"[tiab] OR "moving platform" [tiab] OR "moving surface" [tiab]) AND (Human OR Adult OR adults OR Patient OR patients OR Healthy control∗ OR Healthy subject∗ OR "Humans"[Mesh]) AND ("Back"[Mesh] OR spine[tiab] OR spines[tiab] OR spinal[tiab] OR paraspinal[tiab] OR "low back"[tiab] OR "posture"[tiab] OR "postural"[tiab] OR "motor control"[tiab] OR "Spine"[Mesh:noexp] OR "Intervertebral Disc"[Mesh] OR "Lumbar Vertebrae"[Mesh] OR "Sacrum"[Mesh] OR "Thoracic Vertebrae"[Mesh])).

Appendix B. COSMIN-list (Box B and C)

Box B. Reliability: relative measures (including test–retest reliability, intrarater reliability and intra-rater reliability

Design requirements	Excellent	Good	Fair	Poor
1. Was the percentage of missing items given?	Percentage of missing items described	Percentage of missing items NOT described		
2. Was there a description of how missing items were handled?	Described how missing items were handled	Not described but it can be deduced how missing items were handled	Not clear how missing items were handled	
3. Was the sample size included in the analysis adequate?	Adequate sample size (⩾50)	Good sample size (25–49)	Moderate sample size (15–24)	Small sample size (<15)
4. Were at least two measurements available?	At least two measurements			Only one measurement
5. Were the administrations independent?	Independent measurements	Assumable that the measurements were independent	Doubtful whether the measurements were independent	Measurements were NOT independent
6. Was the time interval stated?	Time interval stated		Time interval NOT stated	
7. Were patients stable in the interim period on the construct to be measured?	Patients were stable (evidence provided)	Assumable that patients were stable	Unclear if patients were stable	Patients were NOT stable
8. Was the time interval appropriate?	Time interval appropriate		Doubtful whether time interval was appropriate	Time interval NOT appropriate
9. Were the test conditions similar for both measurements?	Test conditions were similar (evidence provided)	Assumable that test conditions were similar	Unclear if test conditions were similar	Test conditions were NOT similar
10. Were there any important flaws in the design or methods of the study?	No other important methodological flaws in the design or execution of the study		Other minor methodological flaws in the design or execution of the study	Other important methodological flaws in the design or execution of the study

(*continued on next page*)

Appendix B (*continued*)

Box B. Reliability: relative measures (including test–retest reliability, intrarater reliability and intra-rater reliability				
Design requirements	Excellent	Good	Fair	Poor
Statistical methods 11. for continuous scores: Was an intraclass correlation coefficient (ICC) calculated?	ICC calculated and model or formula of the ICC described	ICC calculated but model or formula of the ICC not described or not optimal. Pearson or Spearman correlation coefficient calculated with evidence provided that no systematic change has occurred	Pearson or Spearman correlation coefficient calculated WITHOUT evidence provided that no systematic change has occurred or WITH evidence that systematic change has occurred.	No ICC or Pearson or Spearman correlations calculated
12. for dichotomous/nominal/ordinal scores: Was kappa calculated?	Kappa calculated			Only percentage agreement calculated
13. for ordinal scores: Was weighted kappa calculated?	Weighted Kappa calculated		Unweighted Kappa calculated	Only percentage agreement calculated
14. for ordinal scores: Was the weighting scheme described?	Weighting scheme described	Weighting scheme NOT described		

Box C. Measurement error: absolute measures				
Design requirements	Excellent	Good	Fair	Poor
1. Was the percentage of missing items given?	Percentage of missing items described	Percentage of missing items NOT described		
2. Was there a description of how missing items were handled?	Described how missing items were handled	Not described but it can be deduced how missing items were handled	Not clear how missing items were handled	
3. Was the sample size included in the analysis adequate?	Adequate sample size (⩾50)	Good sample size (25–49)	Moderate sample size (15–24)	Small sample size (<15)
4. Were at least two measurements available?	At least two measurements			Only one measurement
5. Were the administrations independent?	Independent measurements	Assumable that the measurements were independent	Doubtful whether the measurements were independent	Measurements were NOT independent
6. Was the time interval stated?	Time interval stated		Time interval NOT stated	
7. Were patients stable in the interim period on the construct to be measured?	Patients were stable (evidence provided)	Assumable that patients were stable	Unclear if patients were stable	Patients were NOT stable
8. Was the time interval appropriate?	Time interval appropriate		Doubtful whether time interval was appropriate	Time interval NOT appropriate
9. Were the test conditions similar for both measurements?	Test conditions were similar (evidence provided)	Assumable that test conditions were similar	Unclear if test conditions were similar	Test conditions were NOT similar
10. Were there any important flaws in the design or methods of the study?	No other important methodological flaws in the design or execution of the study		Other minor methodological flaws in the design or execution of the study	Other important methodological flaws in the design or execution of the study
Statistical methods 11. for CTT: Was the Standard Error of Measurement (SEM) of Limits of Agreement (LoA) calculated?	SEM, SDC, or LoA calculated	Possible to calculate LoA from the data presented		SEM calculated based on Cronbach's alpha, or on SD from another population

Box B (Reliability) and Box C (Measurement error) of the COSMIN-list. In question B3 and C3 the needed sample size was adjusted for this study.

References

Andersen TB, Essendrop M, Schibye B. Movement of the upper body and muscle activity patterns following a rapidly applied load: the influence of pre-load alterations. Eur J Appl Physiol 2004;91:488–92.

Aruin AS, Latash ML. The role of motor action in anticipatory postural adjustments studied with self-induced and externally triggered perturbations. Exp Brain Res 1995;106:291–300.

Bazrgari B, Hendershot B, Muslim K, Toosizadeh N, Nussbaum MA, Madigan ML. Disturbance and recovery of trunk mechanical and neuromuscular behaviours following prolonged trunk flexion: influences of duration and external load on creep-induced effects. Ergonomics 2011a;54:1043–52.

Bazrgari B, Nussbaum MA, Madigan ML. Estimation of trunk mechanical properties using system identification: effects of experimental setup and modelling assumptions. Comput Meth Biomech Biomed Eng 2012;15:1001–9.

Bazrgari B, Nussbaum MA, Madigan ML, Shirazi-Adl A. Soft tissue wobbling affects trunk dynamic response in sudden perturbations. J Biomech 2011b;44:547–51.

Bazrgari B, Shirazi-Adl A, Lariviere C. Trunk response analysis under sudden forward perturbations using a kinematics-driven model. J Biomech 2009;42:1193–200.

Blomqvist S, Wester A, Rehn B. Postural muscle responses and adaptations to backward platform perturbations in young people with and without intellectual disability. Gait Posture 2014;39:904–8.

Borghuis AJ, Lemmink KA, Hof AL. Core muscle response times and postural reactions in soccer players and nonplayers. Med Sci Sports Exerc 2011;43:108–14.

Boudreau S, Farina D, Kongstad L, Buus D, Redder J, Sverrisdottir E, et al. The relative timing of trunk muscle activation is retained in response to unanticipated postural-perturbations during acute low back pain. Exp Brain Res 2011;210:259–67.

Brown SH, Haumann ML, Potvin JR. The responses of leg and trunk muscles to sudden unloading of the hands: implications for balance and spine stability. Clin Biomech (Bristol, Avon) 2003;18:812–20.

Brown SH, McGill SM. The intrinsic stiffness of the in vivo lumbar spine in response to quick releases: implications for reflexive requirements. J Electromyo Kinesiol: Off J Int Soc Electrophysiol Kinesiol 2009;19:727–36.

Brown SH, Vera-Garcia FJ, McGill SM. Effects of abdominal muscle coactivation on the externally preloaded trunk: variations in motor control and its effect on spine stability. Spine 2006;31:E387–93.

Carlson H, Nilsson J, Thorstensson A, Zomlefer MR. Motor responses in the human trunk due to load perturbations. Acta Physiol Scand 1981;111:221–3.

Carpenter MG, Allum JH, Honegger F. Directional sensitivity of stretch reflexes and balance corrections for normal subjects in the roll and pitch planes. Exp Brain Res 1999;129:93–113.

Carpenter MG, Thorstensson A, Cresswell AG. Deceleration affects anticipatory and reactive components of triggered postural responses. Exp Brain Res 2005;167:433–45.

Chen CL, Lou SZ, Wu HW, Wu SK, Yeung KT, Su FC. Effects of the type and direction of support surface perturbation on postural responses. J Neuroeng Rehabil. 2014;11:50.

Chiang J, Potvin JR. The in vivo dynamic response of the human spine to rapid lateral bend perturbation: effects of preload and step input magnitude. Spine 2001;26:1457–64.

Cholewicki J, Greene HS, Polzhofer GK, Galloway MT, Shah RA, Radebold A. Neuromuscular function in athletes following recovery from a recent acute low back injury. J Orthop Sports Phys Ther 2002;32:568–75.

Cholewicki J, Juluru K, Radebold A, Panjabi MM, McGill SM. Lumbar spine stability can be augmented with an abdominal belt and/or increased intra-abdominal pressure. Eur Spine J: Off Publ Eur Spine Soc, Eur Spinal Deformity Soc, Eur Section Cervical Spine Res Soc 1999;8:388–95.

Cholewicki J, Lee AS, Peter Reeves N, Morrisette DC. Comparison of trunk stiffness provided by different design characteristics of lumbosacral orthoses. Clin Biomech (Bristol, Avon) 2010a;25:110–4.

Cholewicki J, McGill KC, Shah KR, Lee AS. The effects of a three-week use of lumbosacral orthoses on trunk muscle activity and on the muscular response to trunk perturbations. BMC Musculoskelet Dis 2010b;11:154.

Cholewicki J, McGill SM. Mechanical stability of the in vivo lumbar spine: implications for injury and chronic low back pain. Clin Biomech 1996;11:1–15.

Cholewicki J, Silfies SP, Shah RA, Greene HS, Reeves NP, Alvi K, et al. Delayed trunk muscle reflex responses increase the risk of low back injuries. Spine 2005;30:2614–20.

Cholewicki J, Simons AP, Radebold A. Effects of external trunk loads on lumbar spine stability. J Biomech 2000;33:1377–85.

Cort JA, Dickey JP, Potvin JR. Trunk muscle contributions of to L4-5 joint rotational stiffness following sudden trunk lateral bend perturbations. J Electromyo Kinesiol: Off J Int Soc Electrophysiol Kinesiol 2013;23:1334–42.

Cote JN, Patenaude I, St-Onge N, Fung J. Whiplash-associated disorders affect postural reactions to antero-posterior support surface translations during sitting. Gait Posture 2009;29:603–11.

Cresswell AG, Oddsson L, Thorstensson A. The influence of sudden perturbations on trunk muscle activity and intra-abdominal pressure while standing. Exp Brain Res 1994;98:336–41.

de Vlugt E, Schouten AC, van der Helm FC. Closed-loop multivariable system identification for the characterization of the dynamic arm compliance using continuous force disturbances: a model study. J Neurosci Meth 2003a;122:123–40.

de Vlugt E, Schouten AC, van der Helm FC, Teerhuis PC, Brouwn GG. A force-controlled planar haptic device for movement control analysis of the human arm. J Neurosci Meth 2003b;129:151–68.

Diener HC, Horak FB, Nashner LM. Influence of stimulus parameters on human postural responses. J Neurophysiol 1988;59:1888–905.

Dobosiewicz K. Neurophysiological mechanism of the unloading reflex as a prognostic factor in the early stages of idiopathic adolescent scoliosis. Eur Spine J: Off Publ Eur Spine Soc, Eur Spinal Deformity Soc, Eur Section Cervical Spine Res Soc 1997;6:93–7.

Dupeyron A, Demattei C, Kouyoumdjian P, Missenard O, Micallef JP, Perrey S. Neuromuscular adaptations after a rehabilitation program in patients with chronic low back pain: case series (uncontrolled longitudinal study). BMC Musculoskelet Dis 2013;14:277.

Dupeyron A, Perrey S, Micallef JP, Pelissier J. Influence of back muscle fatigue on lumbar reflex adaptation during sudden external force perturbations. J Electromyo Kinesiol: Off J Int Soc Electrophysiol Kinesiol 2010;20:426–32.

Eriksson Crommert AE, Thorstensson A. Trunk muscle coordination in reaction to load-release in a position without vertical postural demand. Exp Brain Res 2008;185:383–90.

Eriksson Crommert AE, Thorstensson A. Trunk muscle reactions to sudden unexpected and expected perturbations in the absence of upright postural demand. Exp Brain Res 2009;196:385–92.

Essendrop M, Andersen TB, Schibye B. Increase in spinal stability obtained at levels of intra-abdominal pressure and back muscle activity realistic to work situations. Appl Ergonom 2002;33:471–6.

Farahpour N, Ghasemi S, Allard P, Saba MS. Electromyographic responses of erector spinae and lower limb's muscles to dynamic postural perturbations in patients with adolescent idiopathic scoliosis. J Electromyo Kinesiol: Off J Int Soc Electrophysiol Kinesiol 2014;24:645–51.

Forssberg H, Hirschfeld H. Postural adjustments in sitting humans following external perturbations: muscle activity and kinematics. Exp Brain Res 1994;97:515–27.

Gardner-Morse MG, Stokes IA. Trunk stiffness increases with steady-state effort. J Biomech 2001;34:457–63.

Gilles M, Wing AM, Kirker SG. Lateral balance organisation in human stance in response to a random or predictable perturbation. Exp Brain Res 1999;124:137–44.

Goodworth AD, Peterka RJ. Contribution of sensorimotor integration to spinal stabilization in humans. J Neurophysiol 2009;102:496–512.

Goodworth AD, Peterka RJ. Influence of bilateral vestibular loss on spinal stabilization in humans. J Neurophysiol 2010;103:1978–87.

Granata KP, Rogers E, Moorhouse K. Effects of static flexion-relaxation on paraspinal reflex behavior. Clin Biomech (Bristol, Avon) 2005;20:16–24.

Granata KP, Slota GP, Bennett BC. Paraspinal muscle reflex dynamics. J Biomech 2004a;37:241–7.

Granata KP, Slota GP, Wilson SE. Influence of fatigue in neuromuscular control of spinal stability. Hum Factors 2004b;46:81–91.

Gregory DE, Brown SH, Callaghan JP. Trunk muscle responses to suddenly applied loads: do individuals who develop discomfort during prolonged standing respond differently? J Electromyo Kinesiol: Off J Int Soc Electrophysiol Kinesiol 2008;18:495–502.

Grondin DE, Potvin JR. Effects of trunk muscle fatigue and load timing on spinal responses during sudden hand loading. J Electromyo Kinesiol: Off J Int Soc Electrophysiol Kinesiol 2009;19:e237–45.

Gruneberg C, Bloem BR, Honegger F, Allum JH. The influence of artificially increased hip and trunk stiffness on balance control in man. Exp Brain Res 2004;157:472–85.

Hendershot B, Bazrgari B, Muslim K, Toosizadeh N, Nussbaum MA, Madigan ML. Disturbance and recovery of trunk stiffness and reflexive muscle responses following prolonged trunk flexion: influences of flexion angle and duration. Clin Biomech (Bristol, Avon) 2011;26:250–6.

Hendershot BD, Bazrgari B, Nussbaum MA. Persons with unilateral lower-limb amputation have altered and asymmetric trunk mechanical and neuromuscular behaviors estimated using multidirectional trunk perturbations. J Biomech 2013;46:1907–12.

Hendershot BD, Bazrgari B, Nussbaum MA, Madigan ML. Within- and between-day reliability of trunk mechanical behaviors estimated using position-controlled perturbations. J Biomech 2012;45:2019–22.

Henry SM, Fung J, Horak FB. EMG responses to maintain stance during multidirectional surface translations. J Neurophysiol 1998;80:1939–50.

Henry SM, Hitt JR, Jones SL, Bunn JY. Decreased limits of stability in response to postural perturbations in subjects with low back pain. Clin Biomech (Bristol, Avon) 2006;21:881–92.

Herrmann CM, Madigan ML, Davidson BS, Granata KP. Effect of lumbar extensor fatigue on paraspinal muscle reflexes. J Electromyo Kinesiol: Off J Int Soc Electrophysiol Kinesiol 2006;16:637–41.

Hjortskov N, Essendrop M, Skotte J, Fallentin N. The effect of delayed-onset muscle soreness on stretch reflexes in human low back muscles. Scand J Med Sci Sports 2005;15:409–15.

Hodges P, van den Hoorn W, Dawson A, Cholewicki J. Changes in the mechanical properties of the trunk in low back pain may be associated with recurrence. J Biomech 2009;42:61–6.

Hodges PW, Cresswell AG, Thorstensson A. Perturbed upper limb movements cause short-latency postural responses in trunk muscles. Exp Brain Res 2001;138:243–50.

Horak FB, Diener HC, Nashner LM. Influence of central set on human postural responses. J Neurophysiol 1989;62:841–53.
Horak FB, Nashner LM. Central programming of postural movements: adaptation to altered support-surface configurations. J Neurophysiol 1986;55:1369–81.
Horak FB, Nashner LM, Diener HC. Postural strategies associated with somatosensory and vestibular loss. Exp Brain Res 1990;82:167–77.
Huang QM, Hodges PW, Thorstensson A. Postural control of the trunk in response to lateral support surface translations during trunk movement and loading. Exp Brain Res 2001;141:552–9.
Hwang JH, Lee YT, Park DS, Kwon TK. Age affects the latency of the erector spinae response to sudden loading. Clin Biomech (Bristol, Avon) 2008;23:23–9.
Inglis JT, Horak FB, Shupert CL, Jones-Rycewicz C. The importance of somatosensory information in triggering and scaling automatic postural responses in humans. Exp Brain Res 1994;101:159–64.
Jacobs JV, Henry SM, Jones SL, Hitt JR, Bunn JY. A history of low back pain associates with altered electromyographic activation patterns in response to perturbations of standing balance. J Neurophysiol 2011;106:2506–14.
Jones SL, Henry SM, Raasch CC, Hitt JR, Bunn JY. Individuals with non-specific low back pain use a trunk stiffening strategy to maintain upright posture. J Electromyo Kinesiol: Off J Int Soc Electrophysiol Kinesiol 2012;22:13–20.
Kaminski TR, Bock C, Gentile AM. The coordination between trunk and arm motion during pointing movements. Exp Brain Res 1995;106:457–66.
Kamper D, Barin K, Parnianpour M, Reger S, Weed H. Preliminary investigation of the lateral postural stability of spinal cord-injured individuals subjected to dynamic perturbations. Spinal Cord 1999;37:40–6.
Keshner EA, Kenyon RV, Langston J. Postural responses exhibit multisensory dependencies with discordant visual and support surface motion. J Vestibul Res: Equilibr Orientat 2004;14:307–19.
Keshner EA, Woollacott MH, Debu B. Neck, trunk and limb muscle responses during postural perturbations in humans. Exp Brain Res 1988;71:455–66.
Kim Y, Shim JK, Son J, Pyeon HY, Yoon B. A neuromuscular strategy to prevent spinal torsion: backward perturbation alters asymmetry of transversus abdominis muscle thickness into symmetry. Gait Posture 2013a;38:231–5.
Kim Y, Son J, Yoon B. Intensive unilateral neuromuscular training on non-dominant side of low back improves balanced muscle response and spinal stability. Eur J Appl Physiol 2013b;113:997–1004.
Krajcarski SR, Potvin JR, Chiang J. The in vivo dynamic response of the spine to perturbations causing rapid flexion: effects of pre-load and step input magnitude. Clin Biomech (Bristol, Avon) 1999;14:54–62.
Lariviere C, Forget R, Vadeboncoeur R, Bilodeau M, Mecheri H. The effect of sex and chronic low back pain on back muscle reflex responses. Eur J Appl Physiol 2010;109:577–90.
Lavender SA, Marras WS. The effects of a temporal warning signal on the biomechanical preparations for sudden loading. J Electromyo Kinesiol: Off J Int Soc Electrophysiol Kinesiol 1995;5:45–56.
Lavender SA, Marras WS, Miller RA. The development of response strategies in preparation for sudden loading to the torso. Spine 1993;18:2097–105.
Lavender SA, Mirka GA, Schoenmarklin RW, Sommerich CM, Sudhakar LR, Marras WS. The effects of preview and task symmetry on trunk muscle response to sudden loading. Hum Factors 1989;31:101–15.
Lavender SA, Shakeel K, Andersson GB, Thomas JS. Effects of a lifting belt on spine moments and muscle recruitments after unexpected sudden loading. Spine 2000;25:1569–78.
Lawrence BM, Mirka GA, Buckner GD. Adaptive system identification applied to the biomechanical response of the human trunk during sudden loading. J Biomech 2005;38:2472–9.
Lee LJ, Coppieters MW, Hodges PW. En bloc control of deep and superficial thoracic muscles in sagittal loading and unloading of the trunk. Gait Posture 2011;33:588–93.
Lee PJ, Rogers EL, Granata KP. Active trunk stiffness increases with co-contraction. J Electromyo Kinesiol: Off J Int Soc Electrophysiol Kinesiol 2006;16:51–7.
Leinonen V, Kankaanpaa M, Hanninen O, Airaksinen O, Taimela S. Paraspinal muscle responses during sudden upper limb loading. Eur J Appl Physiol 2002;88:42–9.
Leinonen V, Kankaanpaa M, Luukkonen M, Kansanen M, Hanninen O, Airaksinen O, et al. Lumbar paraspinal muscle function, perception of lumbar position, and postural control in disc herniation-related back pain. Spine 2003;28:842–8.
Lund JP, Donga R, Widmer CG, Stohler CS. The pain-adaptation model: a discussion of the relationship between chronic musculoskeletal pain and motor activity. Can J Physiol Pharmacol 1991;69:683–94.
MacDonald D, Moseley GL, Hodges PW. People with recurrent low back pain respond differently to trunk loading despite remission from symptoms. Spine 2010;35:818–24.
MacKinnon CD, Winter DA. Control of whole body balance in the frontal plane during human walking. J Biomech 1993;26:633–44.
Magnusson ML, Aleksiev A, Wilder DG, Pope MH, Spratt K, Lee SH, et al. European Spine Society – the AcroMed Prize for Spinal Research 1995. Unexpected load and asymmetric posture as etiologic factors in low back pain. Eur Spine J: Off Publ Eur Spine Soc, Eur Spinal Deformity Soc, Eur Section Cervical Spine Res Soc 1996;5:23–35.
Mannion AF, Adams MA, Dolan P. Sudden and unexpected loading generates high forces on the lumbar spine. Spine 2000;25:842–52.
Marras WS, Rangarajulu SL, Lavender SA. Trunk loading and expectation. Ergonomics 1987;30:551–62.
Marshall PW, McKee AD, Murphy BA. Impaired trunk and ankle stability in subjects with functional ankle instability. Med Sci Sports Exerc 2009;41:1549–57.
Masani K, Sin VW, Vette AH, Thrasher TA, Kawashima N, Morris A, et al. Postural reactions of the trunk muscles to multi-directional perturbations in sitting. Clin Biomech (Bristol, Avon) 2009;24:176–82.
Mawston GA, McNair PJ, Boocock MG. The effects of prior exposure, warning, and initial standing posture on muscular and kinematic responses to sudden loading of a hand-held box. Clin Biomech (Bristol, Avon) 2007;22:275–81.
McGill SM, Thorstensson A, Norman RW. Non-rigid response of the trunk to dynamic axial loading: an evaluation of current modelling assumptions. Clin Biomech (Bristol, Avon) 1989;4:45–50.
McMulkin ML, Woldstad JC, Hughes RE. Torso loading via a harness method activates trunk muscles less than a hand loading method. J Biomech 1998;31:391–5.
Miller EM, Bazrgari B, Nussbaum MA, Madigan ML. Effects of exercise-induced low back pain on intrinsic trunk stiffness and paraspinal muscle reflexes. J Biomech 2013;46:801–5.
Miller EM, Slota GP, Agnew MJ, Madigan ML. Females exhibit shorter paraspinal reflex latencies than males in response to sudden trunk flexion perturbations. Clin Biomech (Bristol, Avon) 2010;25:541–5.
Mok NW, Brauer SG, Hodges PW. Changes in lumbar movement in people with low back pain are related to compromised balance. Spine 2011;36:E45–52.
Mok NW, Hodges PW. Movement of the lumbar spine is critical for maintenance of postural recovery following support surface perturbation. Exp Brain Res 2013;231:305–13.
Moorhouse KM, Granata KP. Trunk stiffness and dynamics during active extension exertions. J Biomech 2005;38:2000–7.
Moorhouse KM, Granata KP. Role of reflex dynamics in spinal stability: intrinsic muscle stiffness alone is insufficient for stability. J Biomech 2007;40:1058–65.
Moseley GL, Hodges PW, Gandevia SC. External perturbation of the trunk in standing humans differentially activates components of the medial back muscles. J Physiol 2003;547:581–7.
Mullington CJ, Klungarvuth L, Catley M, McGregor AH, Strutton PH. Trunk muscle responses following unpredictable loading of an abducted arm. Gait Posture 2009;30:181–6.
Navalgund A, Buford JA, Briggs MS, Givens DL. Trunk muscle reflex amplitudes increased in patients with subacute, recurrent LBP treated with a 10-week stabilization exercise program. Mot Control 2013;17:1–17.
Newcomer KL, Jacobson TD, Gabriel DA, Larson DR, Brey RH, An KN. Muscle activation patterns in subjects with and without low back pain. Arch Phys Med Rehabil 2002;83:816–21.
Notzel D, Puta C, Wagner H, Anders C, Petrovich A, Gabriel HH. Altered hip muscle activation in patients with chronic non-specific low back pain. Schmerz 2011;25(199–204):206.
Oddsson LI, Persson T, Cresswell AG, Thorstensson A. Interaction between voluntary and postural motor commands during perturbed lifting. Spine 1999;24:545–52.
Omino K, Hayashi Y. Preparation of dynamic posture and occurrence of low back pain. Ergonomics 1992;35:693–707.
Panjabi MM. The stabilizing system of the spine. Part I. Function, dysfunction, adaptation, and enhancement. J Spinal Disord 1992a;5:383–9 [discussion 397].
Panjabi MM. The stabilizing system of the spine. Part II. Neutral zone and instability hypothesis. J Spinal Disord 1992b;5:390–7.
Parcero BP. The in vivo dynamic fatigue response to the spine to sudden loading the sagittal plane: effects of pre-load and step input magnitude. University of Windsor; 2000.
Parnianpour M, Ghosh K, Barin K, Marras WS. Quantification of trunk motion in response to complex platform perturbations while holding weights in an upright posture. Biomed Eng Appl Basis Commun 2001;13:33–46.
Pedersen MT, Essendrop M, Skotte JH, Jorgensen K, Fallentin N. Training can modify back muscle response to sudden trunk loading. Eur Spine J: Off Publ Eur Spine Soc, Eur Spinal Deformity Soc, Eur Section Cervical Spine Res Soc 2004;13:548–52.
Pedersen MT, Essendrop M, Skotte JH, Jorgensen K, Schibye B, Fallentin N. Back muscle response to sudden trunk loading can be modified by training among healthcare workers. Spine 2007;32:1454–60.
Pedersen MT, Randers MB, Skotte JH, Krustrup P. Recreational soccer can improve the reflex response to sudden trunk loading among untrained women. J Strength Cond Res/Nat Strength Cond Assoc 2009;23:2621–6.
Perret C, Robert J. Electromyographic responses of paraspinal muscles to postural disturbance with special reference to scoliotic children. J Manipulative Physiol Ther 2004;27:375–80.
Pigeon P, Yahia LH, Mitnitski AB, Feldman AG. Superposition of independent units of coordination during pointing movements involving the trunk with and without visual feedback. Exp Brain Res 2000;131:336–49.
Portney L, Watkins M. Foundations of Clinical Research: Applications to Practice. NJ: Prentice Hall Upper Saddle River; 2000.
Preuss R, Fung J. Musculature and biomechanics of the trunk in the maintenance of upright posture. J Electromyo Kinesiol: Off J Int Soc Electrophysiol Kinesiol 2008;18:815–28.
Radebold A, Cholewicki J, Panjabi MM, Patel TC. Muscle response pattern to sudden trunk loading in healthy individuals and in patients with chronic low back pain. Spine 2000;25:947–54.
Radebold A, Cholewicki J, Polzhofer GK, Greene HS. Impaired postural control of the lumbar spine is associated with delayed muscle response times in patients with chronic idiopathic low back pain. Spine 2001;26:724–30.
Ramprasad M, Shenoy DS, Sandhu JS, Sankara N. The influence of kinesiophobia on trunk muscle voluntary responses with pre-programmed reactions during

perturbation in patients with chronic low back pain. J Bodywork Movement Ther 2011;15:485–95.
Ramprasad M, Shenoy DS, Singh SJ, Sankara N, Joseley SR. The magnitude of pre-programmed reaction dysfunction in back pain patients: experimental pilot electromyography study. J Back Musculoskelet Rehabil 2010;23:77–86.
Reeves NP, Cholewicki J, Milner TE. Muscle reflex classification of low-back pain. J Electromyo Kinesiol: Off J Int Soc Electrophysiol Kinesiol 2005;15:53–60.
Reeves NP, Cholewicki J, Narendra KS. Effects of reflex delays on postural control during unstable seated balance. J Biomech 2009;42:164–70.
Rietdyk S, Patla AE, Winter DA, Ishac MG, Little CE. NACOB presentation CSB new investigator award. Balance recovery from medio-lateral perturbations of the upper body during standing. North American Congress on Biomechanics. J Biomech 1999;32:1149–58.
Rogers EL, Granata KP. Disturbed paraspinal reflex following prolonged flexion-relaxation and recovery. Spine 2006;31:839–45.
Santos BR, Lariviere C, Delisle A, McFadden D, Plamondon A, Imbeau D. Sudden loading perturbation to determine the reflex response of different back muscles: a reliability study. Muscle Nerve 2011;43:348–59.
Sayenko DG, Masani K, Vette AH, Alekhina MI, Popovic MR, Nakazawa K. Effects of balance training with visual feedback during mechanically unperturbed standing on postural corrective responses. Gait Posture 2012;35:339–44.
Schouten AC, de Vlugt E, van Hilten JJ, van der Helm FC. Quantifying proprioceptive reflexes during position control of the human arm. IEEE Trans Bio-med Eng 2008;55:311–21.
Shu Y, Jiang Z, Xu X, Mirka GA. The effect of a knee support on the biomechanical response of the low back. J Appl Biomech 2007;23:275–81.
Skotte JH, Fallentin N, Pedersen MT, Essendrop M, Stroyer J, Schibye B. Adaptation to sudden unexpected loading of the low back–the effects of repeated trials. J Biomech 2004;37:1483–9.
Stokes IA, Fox JR, Henry SM. Trunk muscular activation patterns and responses to transient force perturbation in persons with self-reported low back pain. Eur Spine J: Off Publ Eur Spine Soc, Eur Spinal Deformity Soc, Eur Section Cervical Spine Res Soc 2006;15:658–67.
Stokes IA, Gardner-Morse M, Henry SM, Badger GJ. Decrease in trunk muscular response to perturbation with preactivation of lumbar spinal musculature. Spine 2000;25:1957–64.
Sung PS, Park HS. Gender differences in ground reaction force following perturbations in subjects with low back pain. Gait Posture 2009;29:290–5.
Sung PS, Spratt KF, Wilder DG. A possible methodological flaw in comparing dominant and nondominant sided lumbar spine muscle responses without simultaneously considering hand dominance. Spine 2004;29:1914–22.
Terwee CB, Mokkink LB, Knol DL, Ostelo RW, Bouter LM, de Vet HC. Rating the methodological quality in systematic reviews of studies on measurement properties: a scoring system for the COSMIN checklist. Qual Life Res: Int J Qual Life Aspects Treat Care Rehabil 2012;21:651–7.
Thomas JS, Lavender SA, Corcos DM, Andersson GB. Trunk kinematics and trunk muscle activity during a rapidly applied load. J Electromyo Kinesiol: Off J Int Soc Electrophysiol Kinesiol 1998;8:215–25.
Thomas JS, Lavender SA, Corcos DM, Andersson GB. Effect of lifting belts on trunk muscle activation during a suddenly applied load. Hum Factors 1999;41:670–6.
Thrasher TA, Sin VW, Masani K, Vette AH, Craven BC, Popovic MR. Responses of the trunk to multidirectional perturbations during unsupported sitting in normal adults. J Appl Biomech 2010;26:332–40.
van der Burg JC, Pijnappels M, van Dieen JH. Out-of-plane trunk movements and trunk muscle activity after a trip during walking. Exp Brain Res 2005;165:407–12.
van der Helm FC, Schouten AC, de Vlugt E, Brouwn GG. Identification of intrinsic and reflexive components of human arm dynamics during postural control. J Neurosci Meth 2002;119:1–14.
van Dieën JH, Cholewicki J, Radebold A. Trunk muscle recruitment patterns in patients with low back pain enhance the stability of the lumbar spine. Spine 2003a;28:834–41.
van Dieën JH, Selen LP, Cholewicki J. Trunk muscle activation in low-back pain patients, an analysis of the literature. J Electromyo Kinesiol: Off J Int Soc Electrophysiol Kinesiol 2003b;13:333–51.
van Drunen P, Maaswinkel E, van der Helm FC, van Dieen JH, Happee R. Identifying intrinsic and reflexive contributions to low-back stabilization. J Biomech 2013;46:1440–6.
Vera-Garcia FJ, Brown SH, Gray JR, McGill SM. Effects of different levels of torso coactivation on trunk muscular and kinematic responses to posteriorly applied sudden loads. Clin Biomech (Bristol, Avon) 2006;21:443–55.
Vera-Garcia FJ, Elvira JL, Brown SH, McGill SM. Effects of abdominal stabilization maneuvers on the control of spine motion and stability against sudden trunk perturbations. J Electromyo Kinesiol: Off J Int Soc Electrophysiol Kinesiol 2007;17:556–67.
Vette AH, Masani K, Wu N, Popovic MR. Multidirectional quantification of trunk stiffness and damping during unloaded natural sitting. Med Eng Phys 2014;36:102–9.
Voglar M, Sarabon N. Reflex delays of the trunk muscles in response to postural perturbations: a reliability study. J Biomech 2014;47:2807–12.
Wagner H, Anders C, Puta C, Petrovitch A, Morl F, Schilling N, et al. Musculoskeletal support of lumbar spine stability. Pathophysiol: Off J Int Soc Pathophysiol/ISP 2005;12:257–65.
Wilder DG, Aleksiev AR, Magnusson ML, Pope MH, Spratt KF, Goel VK. Muscular response to sudden load. A tool to evaluate fatigue and rehabilitation. Spine 1996;21:2628–39.
Zedka M, Kumar S, Narayan Y. Electromyographic response of the trunk muscles to postural perturbation in sitting subjects. J Electromyo Kinesiol: Off J Int Soc Electrophysiol Kinesiol 1998;8:3–10.

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